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HUMAN HEALTH

Local risks and global impacts considering plant-specific functions and constraints: a case study of metal parts cleaning

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Abstract
Background, aim, and scope To achieve sustainable development in industrial processes, attributed chemical risks as well as environmental impacts should be managed. Such non-monetary issues have been analyzed by scientific assessment methodologies such as various risk assessment (RA) and life cycle assessment (LCA) procedures. Local risks to be addressed in RA are microenvironments, including the workplace and neighborhood. Although a comprehensive interpretation of such risks is necessitated in industrial decision making, no practical method has been developed to interpret various types of risk with sufficient understandings of plant-specific functions and constraints. Because elaborate model-based approaches are inevitable for practical process development, actual case studies on chemical risks and detailed plant-specific functions and constraints should be performed. Manufacturing processes require that metal parts must be cleaned in preparation for surface treatments or the completion of metal processing. The significant amount of cleansing agents utilized in cleaning processes has become an issue in Japan. Almost all cleaning processes in Japan are carried out by small- and medium-sized enterprises (SMEs). Machinery processes have not been systematically analyzed in terms of chemical risks and, in addition, the environmental management skills of SMEs are generally far behind those of large enterprises. The objective of this study is to reveal the relationships between chemical risks and plant-specific conditions for a practical risk reduction carried out by industrial decision makers. For this purpose, we aimed at the analysis of such relationships in metal-cleaning processes. Through this analysis, the correlation between local risks and global impacts were discussed in terms of plant-specific conditions.
Materials and methods Through several investigations on cleaning processes, plant-specific functions and constraints were determined with process data required for plant-specific RA and LCA. By plant-specific RA, workers' and neighbors' health risks of inhalational exposure to the utilized cleansing agents were evaluated as unit exposure amount [$mg \cdot kg^{-1} \cdot day^{-1}$] and total exposure amount [$mg \cdot day^{-1}$] in the workplace and neighborhood. As global environmental impacts, human health impacts were evaluated by LCA using disability-adjusted life years through the life cycle of process chemicals including cleansing agents and utilities. On the basis of evaluation results, the relationships among plant-specific conditions and the results were analyzed and discussed by using the results of regression analyses and the Akaike information criterion (AIC).
Results The impacts due to the use of cleansing agents contributed largely to total human health in the LCA results. The results of the functional unit "Cleaning of unit weight of products" demonstrated that the magnitudes of total impacts were not considerably different. In plant-specific RA results, the neighborhood concentrations in some cases were higher than the average concentration in Japan. The neighbors' total exposure amounts were highly connected with the emission amount of cleansing agents and population densities. Because workplace concentrations were different from site-to-site and do not have a simple relationship to the emission amount of cleansing agents, the exposure amounts of workers indicated complicated trends. According to detailed interpretation of all the results, a relationship between occupational exposure and agent emission was revealed. Some devices that enhance the

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process functions became emission factors, such as the local ventilation device installed to keep the workplace safe. Additionally, the shapes of metal parts to be cleaned and cleaning requirements increased the emission of cleansing agents to indoors and outdoors directly. Additionally, some regression analyses and AIC comparisons showed that these plant-specific conditions can be regarded as factors having non-negligible effects on local risks and global impacts.

Discussion In cleaning processes, utilizing various agents to meet cleanliness requirements, plant-specific conditions should be taken into account in their assessments to reduce the chemical risks practically. Constraints from decision makers in the other stages of a product life cycle are unchangeable for on-site engineers in a given process. In this regard, however, the process functions for complying with the requirements originating from the constraints can be managed by on-site engineers. To deal with the risks originating from such factors, operations and devices should be appropriately designed. To achieve such designs, statistical approaches and process understandings should be used in a collaboration to reveal the practical relationship among local risks, global impacts, and process conditions.

Conclusions Local risks and global impacts attributable to metal parts cleaning processes were evaluated in terms of workers' and neighbors' health risks and global human health impacts. A careful interpretation of evaluation results revealed that local risks have features different from those of global impacts. In this paper, we demonstrate that local risks are highly connected with plant-specific conditions. For an appropriate practical implementation of local impacts, as well as plant specification, the characteristics of industrial sectors, including related laws and regulations, should be taken into account to address them from the viewpoint of agent emissions, which can be obtained in ordinary LCA. Otherwise, the data collected in life cycle inventory should be sufficiently expanded to estimate the requirements or to specify an appropriate model.

Recommendations and perspectives The approach to analyze and relate the plant-specific functions and constraints with local risk and global impact can be useful and effective for revealing their factors, which can be supporting information of generating alternatives for reducing them. The application of such an approach can also clarify the plant-specific risk and LCA performance in general. Additionally, the clarified relationship might lead to the increase of the attention of global issues within the decision making including industrial process design and policy making. Several models should be developed for model-based decision making considering plant-specific conditions.

Keywords Human health · Local risks · Metal cleaning · Practical application · Process functions and constraints · Small- and medium-sized enterprises (SMEs)

1 Introduction

In life cycle management (LCM) by industrial decision makers, several evaluation indices should be addressed through assessment methodologies. Local risks, or micro-environmental risks, including occupational and neighborhood risks, must be supervised adequately by process engineers, because they have been considered as a constraint in management of processes utilizing chemicals. Such risks have been addressed by various types of risk assessment (RA) where risks are divided into environment, health, and safety (EHS) categories (Kolluru et al. 1996). In addition to local risk, regional/global environmental impacts should be considered by decision makers. Life cycle assessment (LCA) definitely enables the quantification of such impacts attributable to the life cycle of the utilized chemicals. In the design of processes and operations, local risks and regional/global impacts should be taken into account simultaneously.

Several approaches to the integration of RA and LCA, particularly life cycle impact assessment (LCIA), have previously been carried out. Under the OMNIITOX project, several discussions on the relationship between environmental RA and LCIA have been conducted (Molander et al. 2004). After the OMNIITOX project, environmental RA employs a method of quantifying the environmental risks in a specific area in terms of a unit amount of emission (Larsen 2007). Additionally, LCIA for human health impacts has also been discussed previously (McKone 2006) including the implementation of indoor exposure assessment within the Task Force of the UNEP/SETAC Life Cycle Initiative (Hellweg et al. 2005; Jolliet et al. 2005). With regard to indoor issues, residential impacts have been discussed on the exposure models (Meijer 2005a, b, 2006) and workers' impacts have been addressed in social LCA (Jørgensen 2008). The second version of the life cycle impact assessment method based on endpoint modeling (Research Center for Life Cycle Assessment 2007) includes the indoor exposure impact for a few number of chemicals. These approaches aim to address local risks as one of the impact categories evaluated in LCIA. For carrying out actual risk-based decision making, the method of assessing local and global impacts by separate applications of plant-specific RA and LCA has been proposed (Kikuchi and Hirao 2008a). In this approach, local risks and global impacts are evaluated separately by plant-specific RA and LCA. Both approaches of integrating local risks and global impacts can be accepted on the basis of the requirements of decision making. For more productive discussions on which approach should be applied for a specific decision-making situation, case studies must be conducted on actual decision making in the industrial setting.

Materials utilized as a solvent play a major role in various industrial activities including chemical production, printing,

and machinery manufacturing. In ordinary metal processing, metal parts are greased to avoid possible friction and confrontation during pressing or cutting. The greased process oil and machining swarf are regarded as impurities that should be removed before the subsequent processes. Therefore, a cleaning process is inevitable as the pre- or post-treatment of metal processing (Ministry of the Environment 2007, 2008a). In a cleaning process, however, various cleansing agents have been used and emitted into the environment, and chemical risks associated with these processes have become an issue. As cleansing agents, chlorinated solvents such as dichloromethane (DCM) and trichloroethylene (TCE) have been widely utilized. Both solvents have been applied because of their inexpensiveness, high ability as a cleansing agent, and nonflammability, while a significant amount of emission has become an issue in Japan, as reported in the latest PRTR legislation result (Ministry of the Environment 2008b). In Japan, small- and medium-sized enterprises (SMEs) constitute a significant fraction of metal-parts manufacturers and most metal-cleaning processes are managed by them. The quality of cleaning processes is strongly connected with the functions of metal parts, because the cleaning processes are located after or before metal processing, which adds a key value to the parts such as surface modification, plating and heat treatment.

For metal-cleaning processes, the general risk reductions by technological innovations (von Grote et al. 2003) and environmental assessments by LCA (Kikuchi and Hirao 2008b; European Chlorinated Solvents Association 1996) have been discussed in previous studies. LCA results show that the contribution of the cleaning process to the total environmental impact was considerably large in the life cycle of metal products. Additionally, according to the evaluation results of a running process and alternative scenarios, the occupational risks at a cleaning site have independently the same magnitude of human health impacts as the total life cycle impacts of a cleansing agent (Kikuchi and Hirao 2008a). Even in an assessment of the same plant, a trade-off relationship between them has been found in a previous research (Kikuchi and Hirao 2008a).

Manufacturing processes in SMEs have widely differing conditions including process functions and constraints. Because of the complexity and distinctiveness of risk factors among sites, unified countermeasures cannot yield practical risk reductions in each cleaning site. Local risks and global impacts should be evaluated and interpreted on the basis of plant-specific conditions. On the basis of such plant-specific conditions, the relationship between local risks and global impacts should be analyzed carefully to determine how to evaluate and interpret them comprehensively for decision-making purposes.

In this study, we aim to develop a method of integrating local risk and global impact assessments for risk-based decision making. For this purpose, we analyze and assess 31 different cleaning processes in actual case studies to reveal the relationships among them. On the basis of the results obtained in these case studies, the risk factors are associated with plant-specific conditions, which enables the determination of an appropriate model that interconnects process conditions with local risks and global impacts, and thus, the practical integration of plant-specific RA and LCA.

2 Methods

2.1 Assessments of local risks and global impacts

Figure 1 shows the scope of the assessment of local risks and global impacts of the metal cleaning process. The main phase of this assessment for LCM in industries is the cleaning process where on-site engineers utilize and manage chemicals associated with a process. LCA utilizes process foreground data in the cleaning process, as determined in existing research (Kikuchi and Hirao 2008b). The system boundary includes the life cycle of cleansing agents and the materials for utilities input in all life cycle stages of cleansing agents. The typical life cycle of a cleansing agent is included in Fig. 1 with the description of the targeted life cycle stages and their unit boundaries. “Daily operation of cleaning” and “Cleaning of unit amount of metal parts” were adopted as functional units. The inventory analysis was based on the process foreground data and background data obtained by released databases (Life Cycle Assessment Society of Japan 2008; Japan Environmental Management Association for Industry 2005). LIME second version was applied as the impact assessment method in LCIA, and the indicator was defined as disability adjusted life years (DALY) originating from global warming, air pollution in urban areas, photochemical oxidant creation, and human toxic chemicals, excluding the impact by indoor exposure. DALY is the indicators utilized in existing LCIA methods (Hofstetter 1998; Udo de Haes 2002) and enables the comparison of the results of LCA and plant-specific RA in terms of the same effects, which is human health. Emissions of the following substances with the impact factors for these impact categories are inventoried: for example carbon dioxide, methane, nitrous oxide, sulfur oxides, nitrogen oxides, hydrocarbon, and cleansing agents. The results are shown on the basis of the unit amounts of metal parts (LC-DALY_{kg} [$\text{DALY}\cdot\text{kg}^{-1}$]) and daily operation ($\text{LC-DALY}_{day}$ [$\text{DALY}\cdot\text{day}^{-1}$]).

In the cleaning process shown in Fig. 1, agent consumption (AC), gas-phase agent emission (AE_{gas}), agent emissions such as waste fluid (AE_{wf}), and adsorbed agent on activated carbon (AE_{ac}) are the reference flows taken into account in LCA. Before being emitted into the environment, as described in such reference flows, a part of the vaporized

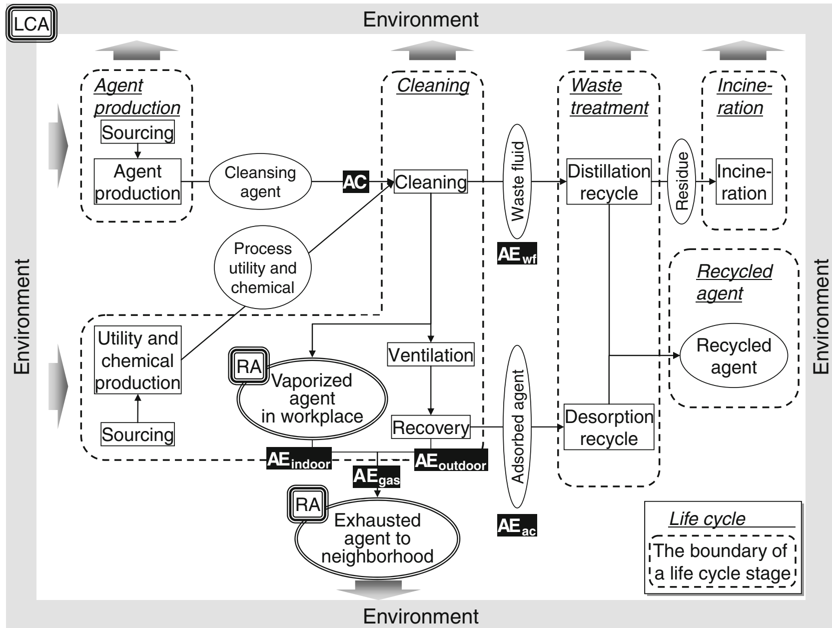


Fig. 1 Scope of assessment of local risks and global impacts of metal-cleaning process

agent fills the workplace (AE_{indoor}) and presents a health risk to workers. As well as such indoor effects, neighborhood risks are caused by AE_{gas} from a cleaning process before diffusing around the regional and global environments. In addition to LCA, plant-specific RA should be carried out simultaneously. According to the existing health risk assessments of DCM and TCE with regard to general exposure in Japan (Nakanishi and Inoue 2005; Nakanishi et al. 2008), their initial exposure route is by inhalation. In this study, we consider the inhalational exposure to the two chlorinated carbons of workers in the workplace and neighbors around cleaning processes.

Several indicators of health risks have been proposed and the selection should be carefully performed in consideration of the aim of the assessments (Kikuchi and Hirao 2008a). In this regard, however, the differences among indicators are mainly caused by the effect analyses in RA. The exposure analyses for several indicators are almost the same. On the basis of this fact, the predicted daily intake (PDI) [mg-intake·kg^{-1}·day^{-1}] and the predicted total exposure amount ($\mathrm{PDI}^{\mathrm{total}}$) [mg-intake·day^{-1}] are evaluated as local risks. Therefore, the indicators of plant-specific RA are set as workers' health risks indicated by $\mathrm{PDI}_{\mathrm{worker}}$ and $\mathrm{PDI}^{\mathrm{total}}_{\mathrm{worker}}$, and neighbors' health risks indicated by $\mathrm{PDI}_{\mathrm{neig}}$ and $\mathrm{PDI}^{\mathrm{total}}_{\mathrm{neig}}$.

$$\mathrm{PDI} = \sum \left(C_{\mathrm{i}} \cdot V_{\mathrm{inh}} \cdot \frac{\Delta t_{\mathrm{exposure,\,i}}}{h_{\mathrm{day}}} \right) \tag{1}$$

$$\mathrm{PDI}^{\mathrm{total}} = N_{\mathrm{exposed}} \cdot \mathrm{BW}_{\mathrm{ave}} \cdot \mathrm{PDI} \tag{2}$$

Here, C_{i} is the concentration of the agent to which the human is exposed ([mg·m^{-3}]), V_{inh} is the inhalation volume per person per day (20 m^3·person^{-1}·day^{-1}), $\Delta t_{\mathrm{exposure}}$ is the exposure time at C_{i} ([h]), h_{day} is hours per day (24 h), N_{exposed} is the number of exposed persons ([person]), and $\mathrm{BW}_{\mathrm{ave}}$ is the average body weight (65 kg·person^{-1}). Workers and neighbors who are exposed to agents at various daily temporal concentrations are defined.

- Workers are exposed to agents at the workplace concentration of cleansing agents (C_{work}) for 8 h/day and at the background concentration in Tokyo for 16 h/day.
- Neighbors are exposed to agents at the concentration of cleansing agents around the cleaning (C_{neig}) site for 24 h.

The C_{work} and the number of exposed workers (N_{work}) are determined from investigations of actual processes. In addition to the data on workers' exposure, the data on neighbors' exposure are collected. C_{neig} is estimated using the emission rate from sites and a dispersion model under local meteorological conditions (Meteorological Office 2003), namely, the Ministry of Economy, Trade and Industry Low-rise Industrial Source Dispersion (METI-LIS) model (Ministry of Economy, Trade and Industry 2006). The defined settings of the dispersion model are the range of calculation, calculated height from ground level, and the value conditions, which are 1 km^2 around a cleaning site, 1.6 m from ground level, and average and maximum concentrations, respectively. The numbers of exposed neighbors (N_{neig}) are set to correspond to the actual population densities of the local area where each site is located.

2.2 Analysis of the relationship between local risk and global impact

To reveal the relationship between the evaluation results of local risks and global impacts, details of the overall emission should be determined, including its distribution route to the environment. Originally, emission amounts are calculated using available data on the site, as shown below.

$$AE_{gas} = AC - (AE_{wf} + AE_{ac}) \tag{3}$$

Here, AE_{gas}[kg·day^{-1}] is the gas-phase agent emission, AC [kg·day^{-1}] is the agent consumption, AE_{wf}[kg·day^{-1}] is the agent emission included in waste fluid, and AE_{ac} [kg·day^{-1}] is the output agent adsorbed on activated carbon. AE_{gas} denotes the total emission, which is the main reference flow in the cleaning process in LCA. The neighborhood risks can be specified by this AE_{gas}, because such risk originates from the total emission from cleaning site. To specify the relationship between local risks and global impacts, the ratio of indoor concentration (C_{indoor}) to AE_{gas} should be determined. In this manner, their distribution factor can be quantitatively expressed using process condition X.

$$\frac{C_{indoor}}{AE_{gas}} = D(X) \tag{4}$$

Here, D (X) [mg·m^{-3}·(kg·day^{-1})$^{-1}$] is the distribution factor of C_{indoor} to AE_{gas}. Because C_{indoor} is the functional parameter of AE_{indoor}, D (X) can also be useful for the analysis of the distribution ratio of AE_{indoor} to AE_{gas}. D (X) means the potential degree of causing indoor exposure originating from unit amount of AE_{gas} from a cleaning process. If D (X) was zero, all emission from the process would be released to the outdoor directly. To specify the relationship between local risk and global impact, D′(X) is defined as the following equation.

$$\frac{PDI_{indoor}}{AE_{gas}} = D'(X) \tag{5}$$

Here, D′(X) [mg-intake·kg^{-1}·day^{-1}·(kg·day^{-1})$^{-1}$] means the degree of indoor exposure for unit amount of AE_{gas} from a cleaning process. Even if the AE_{gas} of two different processes are equal, the higher indoor risk occurred in the process with larger D′(X). In this paper, the relationship between local risk and global impact are analyzed on the basis of Eqs. 4, 5 with measured process conditions.

2.3 Investigation of actual processes

Actual process data The objectives of this investigation were to scrutinize plant-specific conditions as well as the process foreground data required for plant-specific RA and LCA. The collected information is the data required for both assessments, including the average and maximum concentrations around the cleaning machine. The investigation results are organized in the table in "Appendix". The investigated main processes such as cutting, pressing, plating, and heat treatment, have a wide range of variation.

Specification of dominant process functions and constraints Figure 2 illustrates a cleaning process with related material life cycles. In an industrial process, the life cycle of the product and that of the process chemical intersect each other. With regard to the metal cleaning process, the process chemicals are the cleansing agents and the material for the process utility, including electricity, steam, and process water, and the products are the metal parts to be cleaned. The features of input objects, including the metal parts and impurities to be removed, are regarded as the constraints, which are from the upstream stages of the

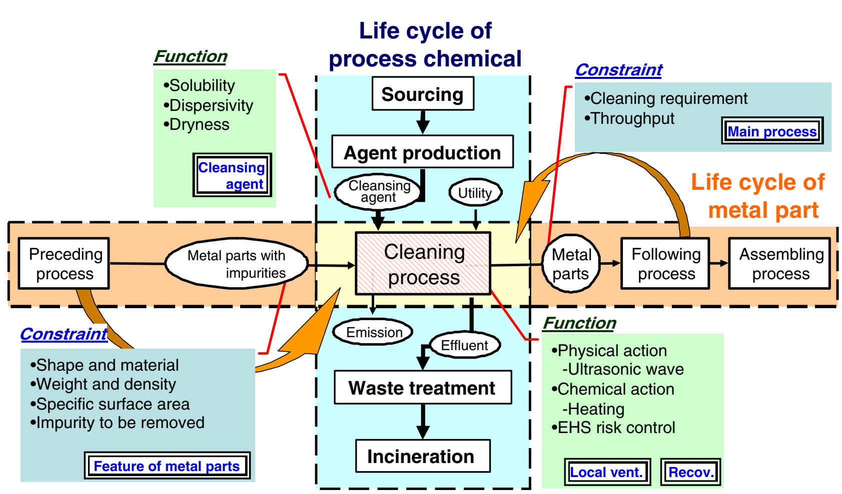


Fig. 2 Process functions and constraints of metal-cleaning process where life cycles of cleansing agents (process chemicals) and metal parts (products) are interconnected

product life cycle. The requirements from the following processes, which are cleaning requirements and throughput, are also constraints. Process devices and operations have been designed to achieve process functions that meet such process constraints. Table 1 organizes the relationships between constraints and functions with required process components. They can be divided mainly into plant-specific and generic components, which can be a factor for local risks and global impacts.

The objective of a cleaning process strongly depends on its relationship with the main process. In the post-treatment performed after cutting or pressing, the cleaning requirements are not always high in relation to the succeeding processes. In contrast, the cleaning pretreatment before metal plating or heat treatment must comply with high cleaning requirements, because the qualities of such metal surface treatment are highly sensitive to the conditions of the metal surface. A small amount of impurities and particles can lead to the failure of surface treatment, and consequently, to the quality of the final products composed of the metal parts. Therefore, a cleaning process has different aspects whether it is a pre- or post-treatment of the main metal processing.

An important type of metal part is manufactured and utilized as the component of products including cars and electronic devices. Metal parts have various shapes and they have been regarded as factors in increasing agent emission. A cleaning site has many types of metal parts that must be cleaned. To deal with such a variety of metal parts, cleaning sites must be applicable to a wide range of shapes and materials of metal parts. The conditions differ from plant to plant, and no two plants have strictly the same plant-specific conditions. The main reason why chlorinated carbons have been widely utilized is their high ability as a cleansing agent; that is, chlorinated carbons can clean various types of metal parts with impurities. However, a cleaning function that is higher than necessary can lead to an increase in the emission amount of cleansing agent, because the enhancement of cleaning functions is usually achieved by increasing the heat input. As well as excess heating, the taken-out agent is regarded as an emission factors attributable to the part's shape. After the drying process in washing machines, the remaining liquid agent on the surface of metal parts is taken out from the washing machine. The agent of such emission is considerably dependent on the part's shape. For the sufficient understanding of cleaning processes, the part's shape should be taken into account in the relativity analyses among plant-specific conditions and risks.

In addition to the part's shape, the number of batches processed per day, or throughput, can increase the amount of the taken-out agent. Almost all SMEs with cleaning process are contractors in the manufacture of products composed of metal parts. Their situations are considerably different from each other, that is, small throughput of small parts or large throughput of large and heavy parts. Their relationship with D (X) should be addressed by combining shape and throughput.

In addition to the plant-specific conditions mentioned above, plant-generic conditions are also taken into account in this study. Their strongest constraints are the laws and regulations imposed on specific industrial sectors utilizing some targeted chemicals. In Japan, the Industrial Safety and Health Law (ISHL) and the Ordinance on Prevention of Organic Solvent Poisoning have regulated the cleaning processes with organic solvents (Ministry of Health, Labor and Welfare 2004). Although the installation of a room-air exchange system is required, the ventilation method and device are determined by on-site engineers, and many sites installed local ventilation systems. There are many types of local ventilation systems, which can be used to classify and divide the investigated 31 processes into three groups. Figure 3 shows the three types of local ventilation systems installed in open-top washing machines, which is conventionally utilized in cleaning processes. The investigations of law-abiding usage of organic solvents are conducted by measuring of workplace concentrations twice a year. There are regulation rates of local ventilation, which can be interpreted as the minimum rate required for local ventilation. With inappropri-

Table 1 Process constraints with functions represented by related parameters to meet them

Conditions	Process constraint	Process function
Plant-specific conditions	Process phase of cleaning Post-treatment of cutting and pressing, pretreatment of surface processing	Cleansing agent, washing devices (chemical and physical effect)
	Cleaning requirement	
	Feature of metal part	
	Material, shape	
	Throughput	
General conditions	Air Pollution Control Law VOC discharge regulation	Recovery system, local ventilation system
	Ordinance on Prevention of Organic Solvent Poisoning	

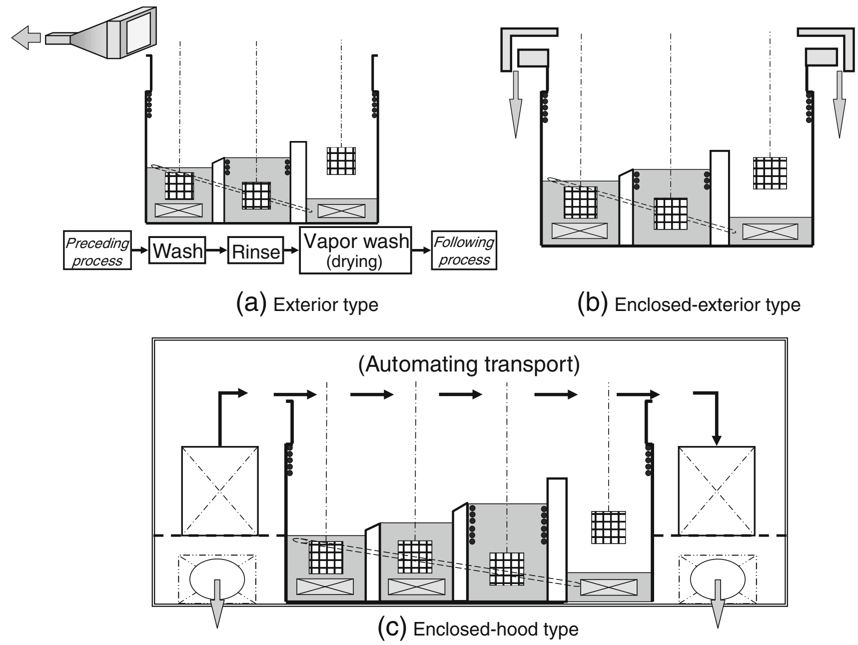


Fig. 3 Open-top washing machines with local ventilation systems

ate local ventilation, the airflow of the ventilation must be increased to meet the requirement. Such airflow can disturb cleansing agents inside the washing machine. The higher rate can reduce all types of risk. If the inlet of the ventilation was installed and the designed shape and position are inadequate, it might result in the increase of C_{indoor} as well as $\mathrm{AE}_{\mathrm{gas}}$.

3 Results

3.1 Local risks and global impacts

Figure 4 shows $\mathrm{LC\text{-}DALY}_{\mathrm{kg}}$, $\mathrm{PDI}_{\mathrm{worker}}$, and $\mathrm{PDI}_{\mathrm{neig}}$. Figure 5 shows $\mathrm{LC\text{-}DALY}_{\mathrm{day}}$, $\mathrm{PDI}^{\mathrm{total}}_{\mathrm{worker}}$ and $\mathrm{PDI}^{\mathrm{total}}_{\mathrm{neig}}$. According to the LCA results in these figures, the cleaning process provides the highest contributions to LC-DALYs, which ranged from 72% to 98%. These figures demonstrated the difference between the profiles of the two LCA results. This is because the throughputs of each process are connected with the agent consumption. Despite the large differences in the process characteristics, the differences in the $\mathrm{LC\text{-}DALY}_{\mathrm{kg}}$ of all processes are smaller than those in the $\mathrm{LC\text{-}DALY}_{\mathrm{day}}$, which correspond to the existing results (Kikuchi and Hirao 2008b).

With regard to the workplace concentration, the standard control concentrations of DCM and TCE are regulated by ISHL, and are 50 and 25 ppm, respectively. Concerning these concentrations, the $\mathrm{PDI}_{\mathrm{worker}}$s of DCM

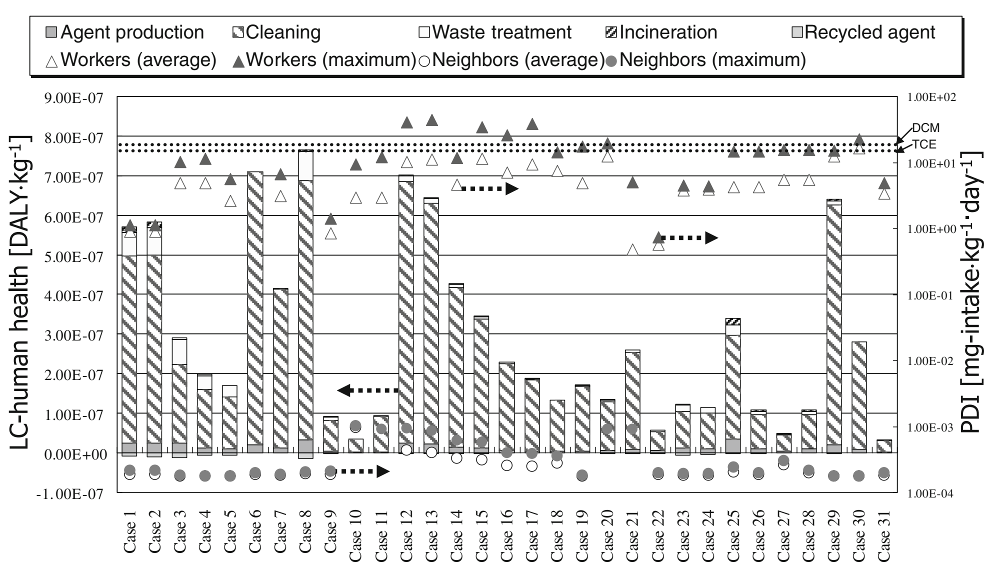


Fig. 4 LC-human health indicated by DALY and the daily intake amounts of workers and neighbors. The functional unit of LC-human health is "Cleaning of unit amount of metal parts". The *dot lines* labeled DCM and TCE means that the $\mathrm{PDI}_{\mathrm{worker}}$s in the workplace with the standard control concentrations, respectively

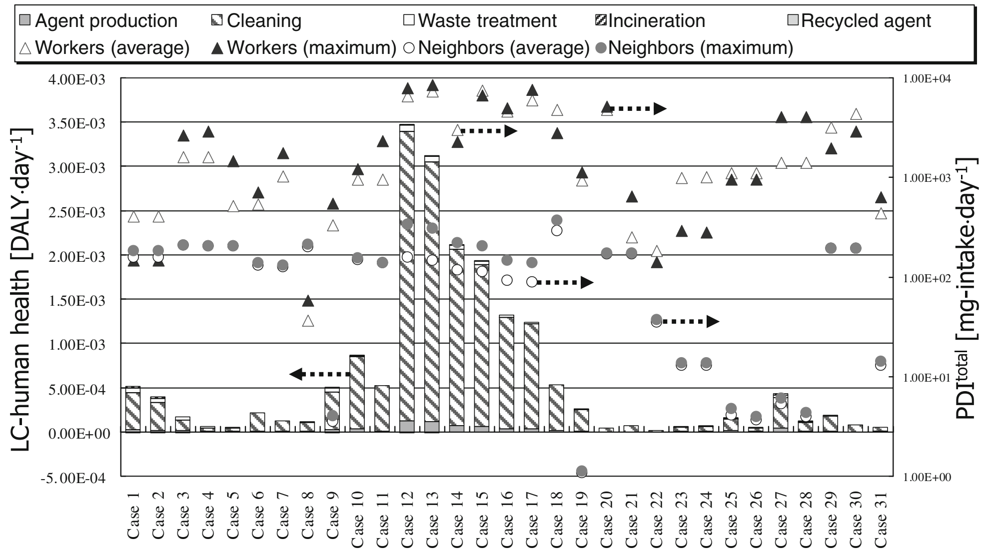


Fig. 5 LC-human health by DALY and the total intake amounts of workers and neighbors. The functional unit of LC-human health is "Daily operation of cleaning"

and TCE are calculated on the assumption that workers are exposed at their standard control concentrations in 8 h·day^{-1} and the average concentration in 16 h·day^{-1}. The results of DCM and TCE are 17.8 mg·kg^{-1}·day^{-1} and 14.0 mg·kg^{-1}·day^{-1}, respectively. A comparison of these values and those in Fig. 4 shows that the average concentrations in all cases are close to the regulation values. In this regard, however, the maximum concentrations caused by cleaning exceed the regulation values in some cases. The PDI_{neig}s in Fig. 4 originate from AE_{gas}, which is the main cause of $LC\text{-}DALY_{day}$s. This is why these values have a similar profile. According to the average exposure amounts of DCM and TCE, which are 8.74E−04 mg·kg^{-1}·day^{-1} and 1.75E−04 mg·kg^{-1}·day^{-1}, respectively, calculated using their average concentrations in Japan (Nakanishi and Inoue 2005; Nakanishi et al. 2008), PDI_{worker}s considerably originated from their workplace exposure. At the same time, it is also demonstrated that the PDI_{neig}s around cleaning processes are non-negligible. In this regard, however, the PDI_{neig}s in Fig. 4 are less than the 92.1 mg·kg^{-1}·day^{-1} and 21.8 mg·kg^{-1}·day^{-1} for DCM and TCE, respectively, which were obtained by the calculation based on the chronic thresholds for both chemicals (Nakanishi and Inoue 2005; Nakanishi et al. 2008). In this calculation, it is assumed that the neighbors are exposed under the threshold concentrations throughout the day. The margins of exposure (MOEs) (Nakanishi and Inoue 2005; Nakanishi et al. 2008; US-EPA 2009) for the initial RA of each case were figured out. They exceeded the uncertainty factors of utilized thresholds, being 100 for both chemicals (Nakanishi and Inoue 2005; Nakanishi et al. 2008). This indicates that there are no significant risks caused by the emitted cleansing agents to neighbors.

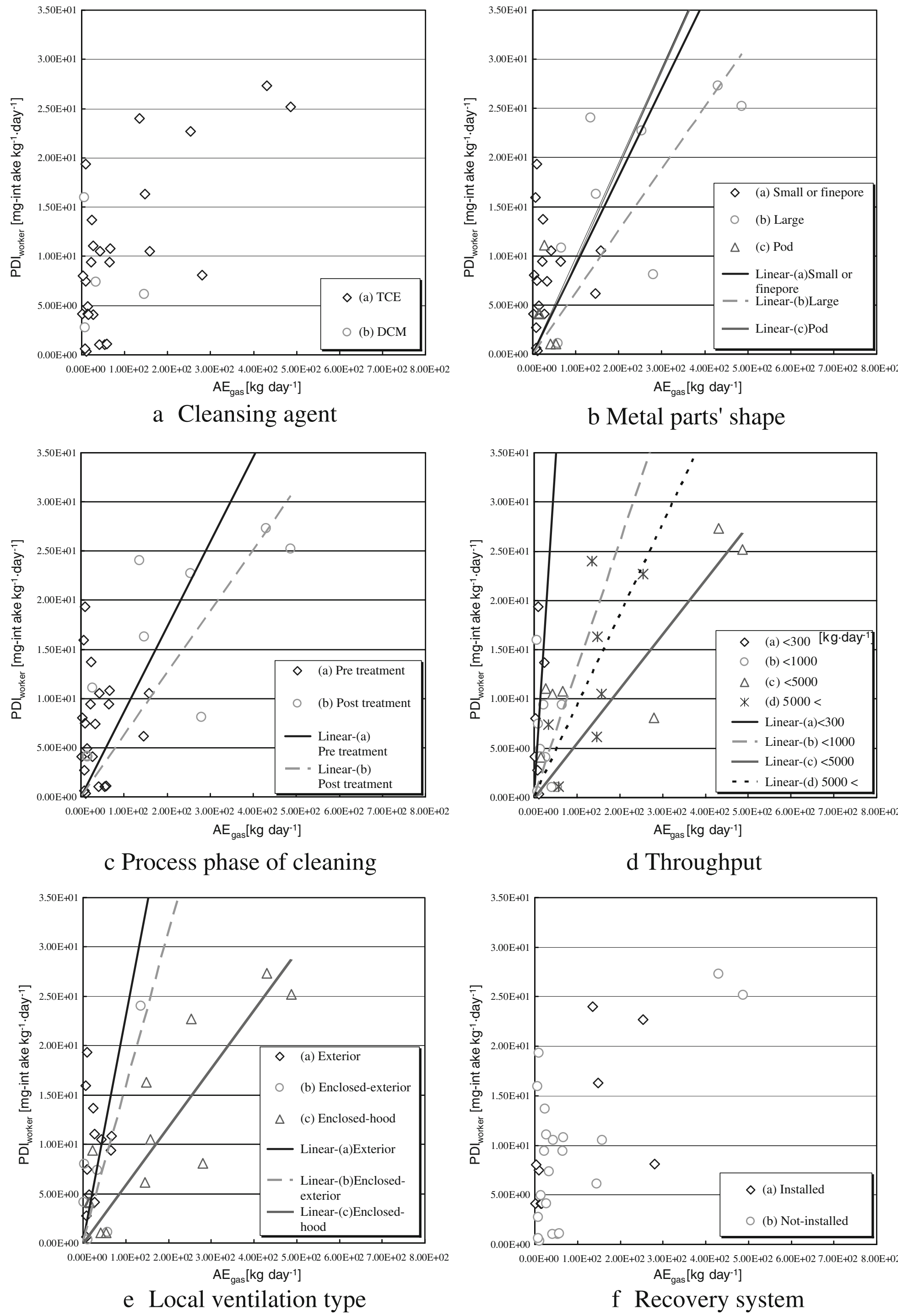
The PDI^{total}_{worker}s shown in Fig. 5 have profiles different from those shown in Fig. 4, because in the evaluation, N_{worker}s, one of the plant-specific conditions, was used. This is the same situation as for the PDI^{total}_{neig}s, which are based on the population densities of each province where each process is found. Although the PDI_{neig}s are much smaller than PDI_{worker}s in Fig. 4, the PDI^{total}_{neig}s and PDI^{total}_{worker}s have the same magnitudes in Fig. 5, because N_{neig}s are higher than N_{worker}s in each process. This is why PDI^{total}_{neig}s are considerably dependent on the location area.

3.2 Plant-based interpretation of conditions

The obtained results were interpreted on the basis of plant-specific and generic conditions. Figure 6 shows the results of analyses on the relationships between AE_{gas}s and PDI_{worker}s for each investigated process based on cleansing agent, metal parts' shape, process phase of cleaning, throughput, local ventilation type, and recovery system. The PDI_{worker}s here are the ones calculated from average workplace concentration in Fig. 5 as the representative value of local indoor risk. Under certain conditions the relativities were confirmed; linear approximation was conducted by the least-squares approach, where all intercepts were set as 0. The results of the regression analyses are organized in Tables 2 and 3.

Cleansing agent Because of the higher ability as cleansing agent, TCE has been more widely adopted for precise cleaning. The diffusivity of the cleansing agent might be dominated by the physical properties of the utilized chemical. As shown in Fig. 6a, however, the weak dependence originating from the difference in the chemical was demonstrated between AE_{gas} and PDI_{worker}. This can be attributed to the fact that in each process, their workplace concentrations were managed so as to be below the standard control values. By operational efforts, the workplace concentrations are controlled to the safe level rather than the expected level based on the diffusivity

Fig. 6 Relationship between total agent emission and PDI_{worker} based on plant-specific conditions



and the emission amount of the chemicals. Because the chemical substances have been considered to have small correlations with AE_{gas}–PDI_{worker} relationships, regression analyses were not performed for data in Fig. 6a.

Characteristics of cleaning process The number of cleaning processes utilizing chlorinated solvents has been reduced because of the voluntary decision of large enterprises to avoid chlorinated chemicals. Most of the remaining processes utilizing such chemicals are the processes where the engineers have many difficulties to comply with cleaning requirements under their individual conditions without chlorinated solvents (New Energy and Industrial Technology Development Organization 2003; Ministry of the Environment 2007). As shown in Fig. 6b, c, chlorinated solvents are needed to comply with the cleaning requirements of the pretreatment process of metal parts with fine and blind pores before the metal surface treatment. Despite the small throughputs and AE_{gas}, such

Table 2 Results of regression analyses between total agent emission and PDI_{worker} with regard to metal parts' shape and process phase

	Metal parts' shape			Process phase	
	Small or pore	Large	Pod	pretreatment	Post-treatment
Coefficients (D'(X))	8.99E−02	6.28E−02	9.60E−02	8.64E−02	6.30E−02
Standard error	3.42E−02	1.09E−02	6.30E−02	2.85E−02	1.03E−02
t stat	2.63E+00	5.79E+00	1.52E+00	3.03E+00	6.14E+00
P value	1.83E−02	6.72E−04	1.88E−01	6.55E−03	1.70E−04
Multiple *R*	5.49E−01	9.09E−01	5.63E−01	5.61E−01	8.99E−01
R squared	3.01E−01	8.27E−01	3.17E−01	3.15E−01	8.07E−01
Adjusted *R* squared	2.39E−01	6.84E−01	1.17E−01	2.65E−01	6.96E−01
Standard error	8.08E+00	8.50E+00	4.89E+00	7.43E+00	7.98E+00
Observations	17	8	6	21	10

cleaning processes result in comparatively high workplace concentrations, as shown in Fig. 6d. According to Fig. 6b and Table 2, the coefficients of metal parts' shape have large uncertainty as shown in the adjusted *R*. This means that the distribution factor D (X) is dependent on not only the shape of metal parts. In the previous investigation (Ministry of the Environment, Japan 2007, 2008a), it has been confirmed that the operation has great possibilities to dominate the distribution of C_{indoor} to AE_{gas}. The overlapping of small parts is regarded as a factor in the increase AE_{indoor} upon the agent attached on metal surface which is taken out from washing machines to the workplace. The same reason can be applied to the metal parts with fine and blind pores. The cleansing agent penetrating the interspaces between parts and pores is considerably difficult to dry out and, therefore, such agents are brought out and released into the workplace. The operational change might improve these risk factors in process. On the other hand, there are some cleaning processes after the cutting or pressing. The cleaning requirements of such a process are also sufficiently high to utilize chlorinated solvents, because of the finishing phase of manufacturing, the enhancement of electric conductivity, and the use as a houseware. These products ordinary have shapes that increase the amount of agent taken out by large or pod type metal parts.

According to the regression analyses results organized in Tables 2 and 3, some process parameters might have correlations with the relationship between AE_{gas} and PDI_{worker}. Although there are small determination coefficients under some process conditions, the metal parts' shape, process phase of cleaning, and throughput were confirmed to be the factors that determine the distribution factors D′ (X) in Eq. 5. Cleaning processes as a pretreatment have a higher potential of increasing the workplace concentration with the same AE_{gas} as for post-treatment processes. This is because higher cleaning quality is required in pretreatment processes.

As mentioned above, the characteristics of the cleaning process have non-negligible correlations with AE_{gas} and PDI_{worker}, although they result from the constraints from the other life cycle stages.

Local ventilation and recovery system Figure 6e shows the correlation with the relationship between AEgas and PDIworker on the basis of the local ventilation system.

Table 3 Results of regression analyses between total agent emission and PDI_{worker} with regard to throughputs and local ventilation type on site

	Throughput ($kg \cdot day^{-1}$)				Local ventilation type		
	<300	<1,000	<5,000	5,000<	Exterior	Enclosed exterior	Enclosed hood
Coefficients (D'(X))	6.77E−01	1.29E−01	5.48E−02	9.21E−02	2.29E−01	1.57E−01	5.87E−02
Standard error	2.50E−01	5.98E−02	9.72E−03	1.63E−02	6.84E−02	3.63E−02	6.43E−03
t stat	2.71E+00	2.16E+00	5.64E+00	5.65E+00	3.35E+00	4.32E+00	9.12E+00
P value	4.20E−02	5.64E−02	1.33E−03	1.32E−03	6.51E−03	7.59E−03	9.54E−07
Multiple *R*	7.72E−01	5.63E−01	9.17E−01	9.18E−01	7.10E−01	8.88E−01	9.35E−01
R squared	5.96E−01	3.17E−01	8.41E−01	8.42E−01	5.05E−01	7.88E−01	8.74E−01
Adjusted *R* squared	3.96E−01	2.17E−01	6.75E−01	6.75E−01	4.14E−01	5.88E−01	7.91E−01
Standard error	7.26E+00	6.21E+00	6.93E+00	6.42E+00	7.83E+00	5.50E+00	5.14E+00
Observations	6	11	7	7	12	6	13

The results indicate that the type of local ventilation device is strongly connected with emission and concentration.

The exterior-type ventilation shown in Fig. 3a is one of the simplest ventilation; the inlet is located near the opening of the washing machine. This type of ventilation sometimes causes a strong disturbance of the inside agent, and then increases the workplace concentration with small agent emission. The enclosed exterior-type ventilation (Fig. 3b) is the improved exterior type, and has the inlet enclosing the opening of the washing machine. This can effectively collect the gas-phase agent running off the edge, because it is heavier than air. The enclosed hood-type ventilation (Fig. 3c) has an all-enclosing hood to cover all emission routes of agents, including liquid agent taken out by metal parts that cannot be easily trapped by the enclosed exterior type. These features correspond to the results in Fig. 6e. With the same emission amount of agent, the workplace concentrations in sites installed with a local ventilation system decrease in the following order: exterior-type, enclosed exterior-type and enclosed hood-type ventilation systems. Their determination coefficients are sufficiently high to confirm the strong correlations with the distribution factor D (X).

With regard to the local ventilation efficiency, the recovery system should be addressed as one of the possible alternative technologies. The relationship can be found in Fig. 6f. The recovery system is an end-of-pipe technology, which can reduce only the emission amount of agent from the chimney of a plant. This means that such technology cannot reduce the emission from the washing machine, but can collect the emitted agent through the exhaust pipe. To increase the recovery amount, the concentration and amount of agent in the exhaust pipes should be increased; this can be achieved by properly designing the ventilation system. Therefore, the recovery system has consequential connections with the distribution factors of indoor and outdoor emissions. The regression analysis was not performed on the recovery system.

The local ventilation discussed in this study is not just room ventilation for the dilution of the concentration of chemicals in workplace. The inlet of the local ventilation is set near the opening of washing machines as illustrated in Fig. 3. The air disturbance around and inside of washing machines is caused by the wind of ventilation. It was clarified through several experiments and empirical reports that stronger local ventilation can cause a higher amount of the emission of cleansing agent (Ministry of the Environment 2007, 2008a; Kikuchi and Hirao 2008a, b). The air disturbance caused by local ventilation can increase the workplace concentration as well as the emission volume, because it can blow away the cleansing agent inside of the washing machines to the workplace. Such an agent cannot be exhausted by local and room ventilation effectively. Therefore, the local ventilation can affect both local risk and global impact.

3.3 Relationship between agent emission and PDI_{worker}

According to the results of regression analyses shown in Tables 2 and 3, the type of local ventilation system has a stronger correlation with the relationship between AE_{gas} and PDI_{worker} than do the other process conditions on which the regression analyses were conducted. Apparently, local ventilation has been regarded as one of the most dominant factors in agent emission in industry. Although the correlation is smaller than that of local ventilation, other process conditions have some relationship with the distribution factor D (X).

To validate the results of the regression analysis, the comparison of the established approximation line was conducted on the basis of the Akaike information criterion (AIC) shown in the following equations. AIC has been applied to compare models in process engineering (Arora et al. 2001; Conner et al. 2005). A smaller AIC means a higher validation of the model. In this study, the residual sum of squares obtained using the regression analysis tool in Microsoft® Excel was adopted for the calculation of the maximum likelihood function.

$$\mathrm{AIC} = -2 \times \log(\text{max of likelihood function}) + 2 \times k \quad (6)$$

$$\log(\text{maximum of likelihood function}) = n \log\left(\frac{\sum e_i^2}{n}\right) \quad (7)$$

Here, k is the number of variable parameters, n is the number of observations, and $\sum e_i{}^2$ is the residual sum of squares. AIC calculations were executed on the basis of multiple relativity analyses grouped into metal parts, process phase, throughput, and local ventilation. The residual sum of squares from each multiple regression analysis is utilized.

Table 4 AIC analysis of the relativity analyses between AE_{gas} and PDI_{worker}

	Metal parts	Process phase	Throughputs	Local ventilation	Base
Σe^2	1.67E+03	1.68E+03	1.18E+03	1.14E+03	1.71E+03
n	31	31	31	31	31
k	3	2	4	3	1
AIC	1.30E+02	1.28E+02	1.21E+02	1.18E+02	1.26E+02

Table 4 organized the AICs of grouped relativity analyses. As a reference value for each AIC, a regression analysis without process conditions was performed and the AIC value was added to Table 4. According to the results, local ventilation and throughput were statistically proven to be factors characterizing the correlation between PDI_{worker} and AE_{gas}. On the other hand, the AICs of the metal parts' shape and the process phase of cleaning were more than that of the base, which means that these conditions have a weak statistical correlation with the distribution factor. In this regard, however, the slight difference among their AICs cannot ensure that they do not correlate with the distribution factor D (X). This is because the raw process data has uncertainty that brings about a change in the AICs.

The D (X) can be interpreted as a composite function of plant-specific conditions. At the same time, plant-generic conditions, such as the standard control values determined by regulation, have forced on-site engineers in order to change the process parameters to comply with the requirements, which resulted in the change in D (X). Although the AIC value can be an index to judge which conditions should be taken into account, a sufficient understanding of the process must be provided to determine a model. As well as plant specification, the characteristics of industrial sectors, including related laws and regulations, should be considered when addressing the relationship between local risks and global impacts.

4 Conclusions

Local risks and global impacts attributable to metal cleaning processes were evaluated in terms of workers' and neighbors' health risks and global human health impacts. The results of local health risks indicated by PDI revealed that such risks are higher than those that originate from the national average concentration. The site dependence of total exposure amounts was clearly demonstrated in the evaluation results, which were calculated by utilizing the actual number of exposed workers and populations. Although the relationships among PDIs, total exposure amounts in microenvironments, and the agent emission as a whole and each unit amount of product were addressed, they were not simple, because several plant-specific conditions are the dominant factors of each evaluation result. To clarify the relationships among process conditions, a careful interpretation of the evaluation results was conducted, and the revealed local risks were found to have features different from those of global impacts. The variety of cleansing agents, the characteristics of the cleaning process, and local ventilation with a recovery system were targeted as the plant-specific conditions that have empirically been regarded as the dominant process conditions dominating the distribution factors of indoor and total emission amounts. The relativity analyses confirmed the strong correlations of such process conditions to agent emission and concentration in microenvironments. At the same time, it could perform the quantification of the empirical understandings on process behavior. The slopes in the results of regression analysis can be interpreted as not only the distribution to indoor or outdoor directly, but also the retention-time of the agent in the workplace. According to the AIC calculations for the conditions, the local ventilation system and throughput in sites have effective correlations with the distribution factors of indoor and outdoor emissions. In this regard, however, as well as statistical approaches, sufficient understanding of the process must be provided to determine the process parameters that should be included and to develop a model. Although the optimal point balancing the process functions and agent emissions might be difficult to determine, the current conditions should be analyzed with the risks associated with agent emission. In this paper, we demonstrated that local risks have strong connections with plant-specific conditions. For an appropriate and practical implementation of local impacts, as well as plant specification, the characteristics of industrial sectors, including related laws and regulations, should be taken into account to determine them from agent emissions which can be obtained in ordinary LCI. Otherwise, the data collected in LCI should be sufficiently expanded enough to estimate the requirements or specify an appropriate model.

The approach to analyze and relate the plant-specific functions and constraints with local risk and global impact can be useful and effective for revealing their factors, which can be supporting information of generating alternatives for reducing them. The revealed qualitative and quantitative relationship among plant-specific conditions, plant-specific risk, and LCA performance might lead to the increase of the attention of global issues within the decision making including industrial process design and policy making. The aspects of the plant-specific conditions can show trade-off relationships between local risk and global impact as shown on the local ventilation system in metal cleaning processes (Kikuchi and Hirao 2008a). Based on the understanding of such process characteristics, effective process alternatives can be discussed in detail. For the model-based decision making considering plant-specific conditions, the analysis of such a relationship has a great role in promoting appropriate life cycle thinking in actual decision making.

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Appendix

Table 5 Process investigation results (Case 1–Case 31)

		Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8	Case 9	Case 10
Process phase of cleaning		Pretreatment (plating)	Pretreatment (plating)	Pretreatment (plating)	Pretreatment (plating)	Pretreatment (plating)	Pretreatment (plating)	Pretreatment (plating)	Pre/post-treatment (heat treatment)	Pre/post-treatment (heat treatment)	Pretreatment (corrosion control)
Cleaning requirement		Precise	Precise	Precise	Precise	Precise	Precise	Precise	Precise	Precise	Normal
Throughput (kg·month^{-1})		1.97E+04	1.48E+04	1.18E+04	5.88E+03	5.88E+03	6.00E+03	6.00E+03	4.50E+03	1.31E+05	4.88E+05
Cleansing agent		TCE	TCE	TCE	TCE	TCE	TCE	TCE	TCE	TCE	DCM
Metal parts	Material	1,2,3,4,5,6,7	1,2,3,4,5,6,7	1,2,3,4,5,6,7,8	1,2,3,4,5,6,7,8	1,2,3,4,5,6,7,8	1,3,4,5,9, 10	1,3,4,5,9, 10	4,5	11	3,7,11
	Shape	d	d	a,b,c,d	a,b,c,d	a,b,c,d	a,b,c,d,e,h	a,b,c,d,e,h	a,b,c,d,e,h	a,b,c,d,e,h,i	a,b,c,d,e,h
Process	Operation	Manual	Manual	Manual	Manual	Manual	Manual	Manual	Hoist	Hoist	Automatic
	Local ventilation	Enclosed hood	Enclosed hood	Exterior	Enclosed exterior	Enclosed exterior	Exterior	Exterior	Enclosed exterior	Enclosed exterior	Enclosed hood
	Recovery	Null	Null	Installed	Installed	Installed	Null	Null	Null	Null	Null
Input (kg·day^{-1})	DCM	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.73E+02
	TCE	9.24E+01	7.41E+01	6.05E+01	1.67E+01	1.31E+01	2.66E+01	1.52E+01	2.08E+01	9.67E+01	0.00E+00
Utility (MJ·day^{-1})	Electricity [kWh·day^{-1}]	8.37E+01	6.28E+01	1.52E+02	5.18E+01	4.35E+01	1.25E+02	1.25E+02	1.71E+02	4.83E+02	5.57E+02
	Kerosene	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Steam (city gas)	9.36E+02	7.12E+02	1.03E+03	3.94E+02	3.62E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Steam (LPG)	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.71E+04
	Steam (kerosene)	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Workplace concentration (mg·m^{-3})	Maximum	1.09E+01	1.09E+01	9.83E+01	1.09E+02	5.46E+01	5.32E+01	6.55E+01	4.37E+00	1.37E+01	9.13E+01
	Average	8.74E+00	8.74E+00	4.75E+01	4.75E+01	2.57E+01	2.69E+01	3.04E+01	2.73E+00	8.19E+00	2.82E+01

	Case 11	Case 12	Case 13	Case 14	Case 15	Case 16	Case 17	Case 18	Case 19	Case 20
Process phase of cleaning	Pretreatment (corrosion control)	Post-treatment (cutting)	Post-treatment (cutting)	Post-treatment (cutting)	Post-treatment (cutting)	Post-treatment (cutting)	Post-treatment (cutting)	Pretreatment (plating)	Post-treatment (pressing)	Pretreatment (coating)
Cleaning requirement	Normal	Normal	Normal	Normal	Normal	Normal	Normal	Precise	Normal	Precise
Throughput (kg·month^{-1})	1.12E+05	9.91E+04	9.68E+04	9.89E+04	1.12E+05	1.15E+05	1.32E+05	8.00E+04	3.00E+04	7.65E+03
Cleansing agent	DCM	TCE	TCE	TCE	TCE	TCE	TCE	TCE	TCE	DCM
Metal parts	3,7,11	1	1	1	1	1	1	2,3,4	12	3,11
	A,b,c,d,e,h	f,i	f,i	f,i	f,i	f,i	f,i	a,b,c,d,e,h,i	c,k	a,c,h,j
Process	Hoist	Automatic	Automatic	Automatic	Automatic	Automatic	Automatic	Hoist	Automatic	Hoist
	Enclosed exterior	Enclosed hood	Enclosed hood	Enclosed hood	Enclosed hood	Enclosed hood	Enclosed hood	Exterior	Exterior	Exterior
	Null	Null	Null	Installed	Installed	Installed	Installed	Null	Null	Null
Input (kg·day^{-1})	3.96E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.13E+01
	0.00E+00	5.43E+02	4.80E+02	3.12E+02	2.83E+02	1.64E+02	1.51E+02	7.31E+01	3.19E+01	0.00E+00
Utility (MJ·day^{-1})	1.33E+02	1.61E+03	1.73E+03	1.73E+03	1.73E+03	4.38E+02	4.38E+02	1.73E+02	5.89E+02	2.30E+02
	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	0.00E+00	0.00E+00	4.74E+02	4.74E+02	4.74E+02	1.70E+04	1.70E+04	3.50E+02	0.00E+00	0.00E+00
	1.51E+04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Workplace concentration (mg·m^{-3})	1.16E+02	3.93E+02	4.24E+02	1.12E+02	3.32E+02	2.49E+02	3.78E+02	1.39E+02	1.69E+02	1.91E+02
	2.82E+01	9.83E+01	1.09E+02	4.53E+01	1.11E+02	6.93E+01	9.01E+01	7.15E+01	4.68E+01	1.20E+02

Table 5 (continued)

	Case 21	Case 22	Case 23	Case 24	Case 25	Case 26	Case 27	Case 28	Case 29	Case 30	Case 31
Process phase of cleaning	Pretreatment (coating)	Pretreatment (coating)	Post-treatment (cutting)	Post-treatment (cutting)	Pre/post-treatment (heat treatment)	Pre/post-treatment (heat treatment)	Pre/post-treatment (heat treatment)	Pre/post-treatment (heat treatment)	Pretreatment (plating)	Pretreatment (plating)	Post-treatment (cutting)
Cleaning requirement	Precise	Precise	Precise	Normal	Precise	Precise	Precise	Precise	Precise	Precise	Normal
Throughput (kg·month^{-1})	6.60E+03	8.16E+03	9.99E+03	1.16E+04	9.36E+03	9.90E+03	1.73E+05	2.27E+04	5.76E+03	5.76E+03	3.30E+04
Cleansing agent	DCM	TCE	TCE	TCE	TCE	TCE	TCE	TCE	TCE	TCE	TCE
Metal parts	3,11	3,11	4	4	3,7,11	3,7,11	3,7,11	3,7,11	1,2,3,4,5	1,2,3,4,5	4
	a,c,h,j	a,c,h,j	b,k	b,k	a,b,c,d,e,h	a,b,c,d,e,h	a,b,c,d,e,h	a,b,c,d,e,h	a,b,c,d,f,h	a,b,c,d,f,h	b,k
Process	Automatic	Hoist	Automatic	Automatic	Hoist	Automatic	Automatic	Hoist	Manual	Manual	Automatic
	Exterior	Exterior	Enclosed hood	Enclosed hood	Exterior	Enclosed hood	Enclosed hood	Exterior	Exterior	Exterior	Enclosed hood
	Null	Null	Installed	Installed	Null	Null	Null	Null	Null	Null	Installed
Input (kg·day^{-1})	1.13E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	0.00E+00	1.01E+01	2.70E+01	2.64E+01	7.23E+01	2.41E+01	1.76E+02	4.82E+01	2.55E+01	1.03E+01	2.01E+01
Utility (MJ·day^{-1})	4.61E+02	2.84E+01	4.48E+01	4.48E+01	9.75E+01	4.40E+01	6.36E+02	2.10E+02	3.20E+01	3.20E+01	7.55E+01
	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.86E+03
	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	0.00E+00	0.00E+00	7.10E+02	1.03E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Workplace concentration (mg·m^{-3})	4.86E+01	7.10E+00	4.37E+01	4.23E+01	1.43E+02	1.43E+02	1.52E+02	1.52E+02	1.47E+02	2.16E+02	4.73E+01
	4.51E+00	5.46E+00	3.70E+01	3.79E+01	4.10E+01	4.10E+01	5.30E+01	5.30E+01	1.20E+02	1.62E+02	3.26E+01

1 Cu, *2* Al, *3* Fe, *4* SUS, *5* brass, *6* bronze, *7* Zn, *8* plastic, *10* Au, *11* Ag, *12* steel, *13* steel with tin-plating, *a* stick, *b* disc, *c* column, *d* plate, *e* ball, *f* pipe, *g* hoop, *h* blind hole, *i* large, *j* concavity and convexity, *k* pod

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